From Basic Ideas to Proof-of-concept Devices

How observations of small “defects” may guide us towards new technology.

Dialogue between Professor Dennis Meier, Postdoc Mariia Stepanova and Ph.D. candidate Erik Lysne. Facilitated by Karen-Elisabeth Sødahl.

Erik Lysne, Dennis Meier and Mariia Stepanova.

Background and motivation

“It all started with a scientific discussion with a colleague at a conference more than a decade ago,” Dennis says. “She was working on the theory of a new magnetic phase that had just been discovered. The discussion sparked my interest in the underlying physics. At that time, I was doing experimental work on remotely related topics and immediately had ideas for first experiments, which then of course did not work out right away. But that is how it goes: Science demands a good mixture of curiosity and patience to tackle the more complex problems. Today, things look different. The initial ideas have evolved into successful fundamental research projects, exploring new opportunities for future nanotechnology.”

The goal of the research team around Dennis is to understand and utilize new discoveries in magnetism at the nanoscale to develop solutions for more efficient low-energy devices. “If you take the memory of a computer, for example, it is basically nothing but a really fancy kind of *rock* into which you *engrave* the information you want to store,” Erik says. “We are exploring novel physics that potentially allow us to *engrave* the 1s and 0s on which modern information technology relies in new ways.”

“It is crucial to understand the underlying physics,” Mariia adds. “We are studying magnetic objects through different imaging techniques at the nanoscale to learn how they behave under different experimental conditions, and how we can control them. One important question is whether or not the magnetic nano-objects we find can be written and erased on demand, so that they can eventually serve as data bits.”

Dennis continues, “But it is also crucial to always keep an eye open for new, unexpected things when doing this kind of research. New discoveries very often start with an observation in an experiment that was actually supposed to test or verify something totally different. This makes fundamental research so exciting and important.”

The latter can be seen from the team’s current project, where scientific curiosity and unexpected discoveries have led them to the development of new concepts for memory technology, which they could not even imagine themselves just three years ago.

The research process

“We got inspired by an emergent and rapidly evolving field of research and performed rather target-oriented experiments. But these experiments did not go as we had hoped,” Dennis says. “Unexpected outcomes, however, are quite often the most interesting ones, and step by step we realized that we had discovered something new instead, which nobody had looked at in detail before. Thus, what we first considered a non-successful experiment turned out to be the beginning of a new and exciting journey away from the mainstream. In a sense, this was a lucky coincidence, but also the natural consequence of carefully performed experiments, frequent brainstorming, and dedicated work in the laboratory.”

> *The three of us are part of a much bigger team. We could name so many who are contributing. If you take a piece out of the puzzle, it is not complete anymore and that`s the same with our work. - Dennis*

What the team had found was a novel type of magnetic defect structure that arises at the nanoscale. “The more data we took,” says Dennis, “the more we realized how exciting this was and that these magnetic nano-entities had never been studied before. While publishing our first articles on their fundamental physics, we already developed ideas how our observations could be utilized in devices and started dreaming a little of how they might even improve existing technologies.”

That was the starting point of several scientific proposals the team submitted, which enabled the systematic studies they performed over the past four years at NTNU. These studies allowed them to develop the necessary understanding and expand their skillset, which was essential in order to bring the new discoveries closer to applications and devise first proof-of-concept experiments.

What did we discover and why is it important?

“Usually, when we hear the word *defect* in our daily life, it has a negative connotation. The same used to be true in materials science and especially in information technology, where defects are truly unwanted companions because they are one of the main reasons for failure,” Erik explains. “But this typically refers to defects in the structure of a material, like a missing atom or an atom in the wrong place,” Mariia emphasizes. “What we are studying are defects in the magnetic order, where some of the electrons have a spin that is pointing in the wrong direction. Such magnetic imperfections can be extremely small, down to the length scale of a few atoms. Despite their smallness, these defects cannot just vanish and are thus very robust. This is exactly what we want in our search for objects that we can use to store information: they need to promote ultra-small feature size for high storage density and, of course, non-volatility so that we do not lose our data.”

The idea to make use of magnetic defects – or magnetic solitons, which is the same but sounds more positive – was already established when the team got started and scientists around the world were intensively studying tiny magnetic whirls, so-called skyrmions, as next-generation information carriers.

Dennis elaborates, “Originally, we tried to do the same, but did not manage to observe the magnetic whirls in our model material. This forced us to constantly improve our setup and the experimental strategy, and eventually we measured a large variety of exotic magnetic defects beyond skyrmions which we hadn`t expected.”

Over time, they realized that they had discovered a zoo of novel magnetic defects which share many of the physical properties with the whirls most of the other researchers in the field were investigating. “Although we did not really find what we were looking for, we were kind of lucky and, instead, observed completely new nano-entities that added promising and unforeseen aspects to the existing research.”

Based on these defects and other magnetic imperfections at the nanoscale the team measured later on, they developed different ideas for novel device concepts, which they are currently trying to realize in their laboratory.

How would you describe this joint process of developing new knowledge?

“I would describe it as an interactive process,” Erik explains. “You can start to work in one direction and then you see something weird. First you check that it is not just an artefact and if others have seen the same thing. Sometimes they have, sometimes they haven’t.” Mariia continues, “We build up on the knowledge from previous research, our experience, and collaborations with others. We start our own experiments and go one way, then possibly sideways; every now and then you don’t really know anymore what to measure next and get new input to try new things you did not consider before.”

Dennis adds, "The exchange with other scientists is really crucial. Very often, we measure things at the nanoscale that we do not understand right away, because the physics at this length scale can be truly counterintuitive. In the really complex cases, the data we collect can serve as input to develop a first model together with our colleagues in the theory field, which we then test again in the laboratory and refine step by step until we are sure what`s going on. That's why it is great to be part of a vibrant Center like QuSpin, where such synergetic scientific work and discussions are basically the daily business, allowing to answer complex research questions much more efficiently."

> *As a Ph.D. student and a Postdoc, you think you know everything, but you really don't. So every now and then it is good to have a professor who has more experience around who tells you, "this is not how you do it", or reminds you that you forgot an effect or something. - Mariia*

What is your approach when meeting challenges?

Mariia and Erik joined the project in 2017, when the basic physical properties of the new magnetic defects which Dennis and his collaborators had discovered were already fairly well understood. The plan was to start controlling their motion in the next step, which is one of the key requirements when it comes to applications. But while preparing samples for the experiment, they met a problem: the surface of the material degraded much too fast during nano-structuring – on the timescale of hours – which made it impossible to build the envisioned test devices before the material was magnetically *dead*. But how to protect the surface of a material without covering up the already hard-to-detect magnetic nano-objects the team was interested in? What started out as a seemingly straightforward microscopy study suddenly turned into a materials engineering problem…

"After we realized that, we sat down and discussed new strategies," Dennis explains. "Erik had the idea to shift the focus to another material, which he had already investigated a little together with Markus Altthaler, who is doing his Ph.D. at the University of Augsburg and partly with us at NTNU. This is one of the international collaborations we have with researchers in Germany, Switzerland, Japan and the US, through which we have access to the important high-quality materials needed for our work and to conjointly realize measurements we couldn`t do just by ourselves."

"In parallel, I teamed up with a collaborator at the University of Stuttgart to identify possibilities to continue the originally intended line of research," Mariia mentions.

Thus, once again, an unforeseen challenge required an adjustment of the team's original research plan. "At first, this always feels like a throwback," Dennis says, "but it rarely is – in fact, occasions like this can be very beneficial for the research as we are enforced to take a step back, brainstorm, critically re-think the experiments, and develop new ideas. For me, this problem-solving as a team is one of the most enjoyable tasks in our job – a kind of trivia game that we can only master together."

"Yes, although Erik and I went in different directions, we still asked each other for advice, discussed with Dennis and the other team members," Mariia adds. "We performed simulations together, communicated about the open challenges and the progress. Collaborations are so important, and in our group, they happen naturally, which is very helpful whenever a challenge comes up."

From millimeter-sized little rocks to concepts for future technology

When asked a bit more in depth about their recent findings and how one can understand them, Erik says, "I brought this," and puts a small unremarkable stone on the table. The stone is greyish and is about one millimeter in diameter – at first glance, nothing that would catch our attention, but Erik knows better. "This is the material I started studying as an alternative to the one that degraded too fast. Out of this little stone, we are cutting tiny rings with a width that is 100 times thinner than a human hair. Because the magnetic order in the material strongly depends on shape and size, we can control it by cutting such rings. We have learnt how to make the rings with nanometer precision to influence the magnetic order in exactly the way we want, achieving the small and stable magnetic defects it takes to store information."

Presenting the illustration (see next page), Erik explains further, "This is an example of one of the rings and the microscopy measurements we are performing on them. The two colors represent the magnetic order. When regions appear bright, we know that the magnetization points up and when they are dark, the magnetization points down. In reality, the interpretation is more complex, but this is essentially how we visualize magnetic order at the nanoscale and find the tiny magnetic defects Dennis talked about."

Mariia also has a success story to tell. She has found a solution to stop the degradation of the material she and Erik started out with. In addition, together with her international colleagues and with support from Professor Arne Brataas and researcher Alireza Qaiumzadeh at QuSpin, she has demonstrated a conceptually new method for reading out magnetic nanoscale defects, which the team is currently writing up for publication.

"I think this nicely exemplifies what we mentioned before," concludes Dennis, "Progress in science is usually not *linear* and we may have to adapt our ideas several times and make adjustments, but not giving up and looking for solutions always pays off."

Is this how we will store data in the future?

"Well, that's what we are trying to find out," Erik responds. "What you see here is where we left off the day the COVID lockdown hit us. In my simulations, it already works – so theoretically it should definitely be doable. The experimental results are also highly reproducible, the magnetic structures are stable at room temperature and way above, and upscaling is possible, too."

Dennis continues, "This means that, in principle, all ingredients needed to make a proof-of-concept device are in place and I am also convinced that we will be able to do so in the next months. However, this does not mean that you will be able to buy our device next year or that it can really outperform existing technology. Our job is to demonstrate and explain the new physics that enable novel device concepts and show that it is feasible to go this way. We are still doing fundamental science, but with a clear technological motivation."

What's next?

Until recently, the team focused on a *top-down* approach, cutting their nanostructures out of a much larger material. "This is not how it is done when producing actual devices," Erik says, "Instead, one would synthesize optimized thin films with the desired physical properties."

> *I still think it is fun and I believe that it will be possible to realize our initial vision. - Erik*

In order to go in this direction, the groups of Dennis Meier and Christoph Brüne have teamed up. In QuSpin's new laboratory for molecular beam epitaxy (MBE), led by Christoph, Payel Chatterjee and Longfei He are exploring possibilities to grow the materials of interest with atomic-layer precision. Bringing these two lines of research together and combining thin-film and lithography methods would be a major breakthrough, establishing a scalable approach for the fabrication of their test devices.

All this is happening on campus at NTNU and, as Dennis points out, reflects the outstanding infrastructure the team has access to, allowing them and their collaborators to realize projects that bridge materials synthesis, characterization, and device fabrication. "It is not just what we have available in our laboratories; in addition, there is NTNU NanoLab which is crucial for us and where we can become really creative," says Dennis and continues with a smile, "So maybe I was wrong earlier and you will be able to buy our device next year after all".

Magnetic domain pattern in a nano-structured ring. The contrast indicates the direction of the magnetization (dark: up; bright: down).